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TECHNICAL NOTE

Evaluating elbow osteoarthritis within the prehistoric Tiwanaku state using generalized estimating equations (GEE)

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Abstract

Objectives: Studies of osteoarthritis (OA) in human skeletal remains can come with scalar problems. If OA measurement is noted as present or absent in one joint, like the elbow, results may not identify specific articular pathology data and the sample size may be insufficient to address research questions. If calculated on a per data point basis (i.e., each articular surface within a joint), results may prove too data heavy to comprehensively understand arthritic changes, or one individual with multiple positive scores may skew results and violate the data independence required for statistical tests. The objective of this article is to show that the statistical methodology Generalized Estimating Equations (GEE) can solve scalar issues in bioarchaeological studies.

Materials and methods: Using GEE, a population-averaged statistical model, 1,195 adults from the core and one colony of the prehistoric Tiwanaku state (AD 500–1,100) were evaluated bilaterally for OA on the seven articular surfaces of the elbow joint.

Results: GEE linked the articular surfaces within each individual specimen, permitting the largest possible unbiased dataset, and showed significant differences between core and colony Tiwanaku peoples in the overall elbow joint, while also pinpointing specific articular surfaces with OA. Data groupings by sex and age at death also demonstrated significant variation. A pattern of elbow rotation noted for core Tiwanaku people may indicate a specific pattern of movement.

Discussion: GEE is effective and should be encouraged in bioarchaeological studies as a way to address scalar issues and to retain all pathology information.

KEYWORDS

activity reconstruction, bioarchaeology, biomechanics, degenerative joint disease, generalized linear model statistics

1 | INTRODUCTION

Analysis of osteoarthritis (OA), also known as degenerative joint disease with articular cartilage loss and concomitant bone changes, presents one route to understand ancient and modern human populations. OA affects whole joint (i.e., cartilage and bone) structure and function through a multifactorial process in which mechanical factors have a central role (Hunter & Felson, 2006, p. 639). Modern clinical studies show systemic influences, such as age (higher risk in older individuals), sex (higher risk in females, especially postmenopausal women), nutrition (more antioxidants lower risk), genetics, and bone density (osteoporosis increases risk) influence susceptibility to OA (Anderson & Loeser, 2010; Brandt, Dieppe, & Radin, 2009; Dieppe, 1995; Felson et al., 2000). Biomechanical factors like obesity, previous joint damage, mechanical loading, and repeated movements are also part of OA pathogenesis (Allen et al., 2010; Anderson & Loeser, 2010; Cushnaghan & Dieppe, 1991; Dieppe, 1995; Felson, 2004; Felson et al., 1991, 2000; Felson & Zhang, 1998; Gramstad & Galatz, 2006; Hunter & Felson, 2006; Hunter, March, & Sambrook, 2002; Jensen, 2008; Spahn et al., 2017; Teichtahl et al., 2015; Yucesoy, Charles, Baker, & Burchfiel, 2015; Zhang et al., 2017). Thus, a combination of risk factors, skeletal structure, and movement all act on OA causation and location in the body.

In prehistoric human populations where only skeletal remains are present, causation is harder to address. OA has associated pathological bone changes, such as marginal outgrowths or lipping, osteophyte development, sclerosis, porosity, and/or eburnation (Brandt et al., 2009; Dieppe, 1995; Felson et al., 2000; Hunter & Felson, 2006;

Rogers, Waldron, Dieppe, & Watt, 1987), which can be used to identify the prevalence of this condition in archeological human remains. However, how to interpret these changes is in question within paleopathological literature, especially considering OA's multifactorial etiology. Concerns have lead researchers to suggest using (a) a population-focused procedure, (b) a well-contextualized approach, and (c) strong statistical methods to provide more accurate information about past groups, especially concerning the biomechanical influences of OA (Becker, 2013, 2017, 2019; Becker & Goldstein, 2017; Benjamin et al., 2006; Domett, Evans, Chang, Tayles, & Newton, 2017; Jurmain, 1999; Jurmain, Alves Cardoso, Henderson, & Villotte, 2012; Milella, Cardoso, Assis, Lopreno, & Speith, 2015; Nikita, 2014; Pearson & Buikstra, 2006; Villotte & Knüsel, 2013; Weiss & Jurmain, 2007). A population-based approach may be able to address mechanical loading or the repetitive nature of OA in cases where systemic etiology can be held constant. For example, researchers could evaluate a more closed genetic population who live in close regional proximity and share the same cultural identity, assuming similar genomic OA risk and that nutritional intake and obesity risk are comparable among the sample group. Any skeletal remains with injury or osteoporosis could be reported, but OA data excluded in these population-level analyses. In addition, while overall frequency can be evaluated, females and males and age at death must also be assessed to help address concerns with sex and age-related OA. Thus, population-level studies may be able to address biomechanical factors with OA, especially mechanical loading or repetitive movement in past populations, within specific parameters. In addition, any inferences made with this approach would also contextualize findings with other archeological and bioarchaeological data, such as stress, diet, and lifestyle, as part of the interpretation of these population-level OA changes (e.g., Austin, 2017; Becker, 2013, 2017, 2019; Becker & Goldstein, 2017; Cheverko & Bartelink, 2017; Domett et al., 2017; Palmer, Hoogland, & Waters-Rist, 2016; Schrader, 2012).

Methodologically, there is currently not one way to evaluate OA to achieve contextualized population-level results in studies of human skeletal remains. Instead, bioarchaeologists have focused on a variety of ways to evaluate these physical changes on the skeleton (see Anderson & Loeser, 2010; Baker & Pearson, 2006; Becker, 2016; Becker & Goldstein, 2017; Chammas, 2014; Cheverko & Bartelink, 2017; Domett et al., 2017; Klaus, Larsen, & Tam, 2009; Molnar, Ahlstrom, & Leden, 2011; Palmer et al., 2016; Rando & Waldron, 2012; Schrader, 2012; Valderrabano, Horisberger, Russell, Dougall, & Hintermann, 2008; Watkins, 2012; Weiss & Jurmain, 2007 and others). Predominant in these approaches are questions concerning how to evaluate the multiple OA data points collected, and how to analyze these data effectively in ways that can be interpreted usefully. In general, when OA data are collected and analyzed solely by individual, a total average score may result in a loss of specific pathology in various areas of the body. Data would show the condition's frequency in a population or among individuals within a sample, but not where in the body or if there was a pattern to OA data in various articular joints. Alternately, if data are analyzed by an individual joint, such as the elbow joint, the resulting information may not identify changes to key articular surfaces within a joint that could describe a potential biomechanical pattern of directional or repetitive movements. However, if each articular surface is calculated on a per data point basis, such as each of the seven articular surfaces within an elbow joint, one individual with multiple positive scores may skew statistical results making the prevalence of the condition much higher in the population than it truly is. This would also likely be a violation of the independence of data required for many statistical tests. Additionally, evaluating by each articular surface point may be too data heavy, resulting in a list that overwhelms a comprehensive study of past human lifeways.

To combat these scalar issues, along with advocating for a contextualized population-based approach, this article addresses the third concern and argues for using strong statistical methods in the form of the Generalized Estimating Equations (GEE) procedure. GEE is a population-averaged method accounting for correlation among measures within subjects (Agresti, 2007; Ghislatta & Spini, 2004; Liang & Scott, 1986). GEE calculates model estimates of population parameters using individually recorded data points. Each of these data points remains linked to the individual, thus preserving individual level information and retaining the largest possible sample size (Ghislatta & Spini, 2004). As there may be no option to increase the sample population due to limits on cemetery excavation or access to additional museum collections, GEE maximizes the data present. GEE also is flexible enough to accommodate variables that are not normally distributed, small sample sizes, and randomly missing or unobservable variables, all of which are common in research on human skeletal remains. While GEE is not new to bioarchaeological studies and has been effective in evaluating changes in oral health (Gagnon, 2006, 2008; Gagnon & Becker, 2019; Gagnon & Wiesen, 2013), it has been used less often to evaluate other types of skeletal pathology (Becker, 2013, 2017; Becker & Goldstein, 2017; Nikita, 2014; Nikita, Mattingly, & Mirazón Lahr, 2013).

To demonstrate the efficacy of the population-based GEE statistical approach, evidence of OA in the elbow joint was used. The study sample population is from the prehistoric Tiwanaku state (AD 500–1,100) and split into two groups, the heartland core of the state in the Lake Titicaca region of Bolivia and the Tiwanaku colony in the Moquegua Valley of Peru, to perform these model-based population comparisons (Figure 1). While culturally and genetically linked, the two areas represent a difference in approximately 2,300 m.a.s.l., which have shown contrasts in traditional daily tasks, such as high-altitude farming using raised fields versus lower-elevation riverine farming (Becker, 2013, 2016, 2017, 2019; Becker & Goldstein, 2017; Berryman, 2011; Goldstein, 2005, 2012; Janusek, 2004, 2008; Knudson, 2008; Knudson & Blom, 2011; Knudson, Goldstein, Dahlstedt, Somerville, & Schoeninger, 2014; Knudson, Price, Buikstra, & Blom, 2004; Somerville et al., 2015). Thus, evaluating OA evidence from these two genetically similar sample populations from disparate climates and elevations can provide a good case study of the GEE statistical approach. Further, this research demonstrates GEE's value by showing results for each of the seven individual articular surfaces in the elbow joint (Table 1 and Figure 2) and for one combined joint surface in the elbow. For comparison, elbow OA frequency provided on a present or absent basis by score and by individual, with two-by-two contingency table comparisons, looks for frequency and significance. Odds ratio statistical data also shows another statistical method often used in bioarchaeology. Finally,

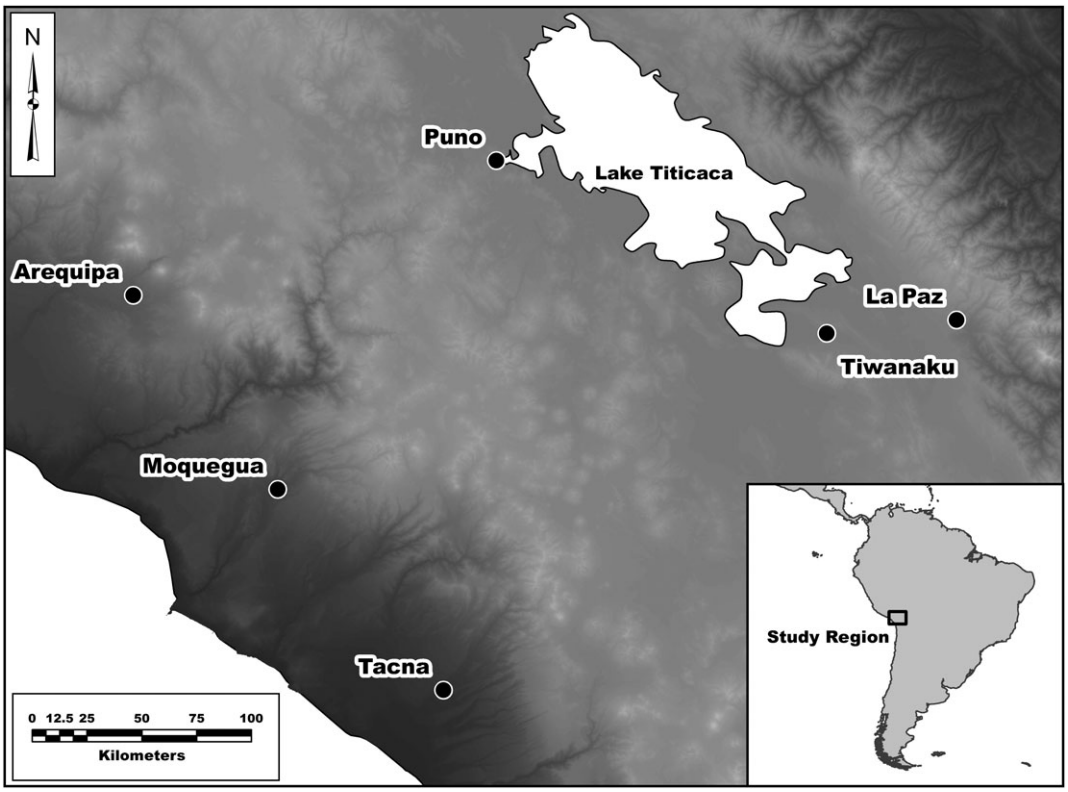

FIGURE 1 Map of the study area

while this research is primarily limited to evidence of elbow joint OA, GEE demonstrates how this methodology accommodates multiple areas of the body, like the arm (articular surfaces in the joints of the shoulder and elbow) and leg (articular surfaces in the joints of the hip and knee) (see Table 1) to discuss its potential in combined bodily areas as a way to address biomechanical movement depending on what questions a researcher asks.

2 | MATERIALS AND METHODS

The study sample consists of 1,195 adults, age 16 years at death and older (Table 2). Highland core Tiwanaku individuals are housed in the town of Tiahuanaco, Bolivia. Data were collected from these 503 adult individuals and the remains are in fair to good condition. The colony samples of 692 adult individuals are housed in Moquegua, Peru and are generally in good to excellent condition. Age and sex were estimated from these skeletal remains using multiple methods. Age at death estimates focused on dental eruption, dental wear, epiphyseal and endocranial suture closure, and visible changes in the pubic symphysis, auricular surface, and sternal rib ends (Brothwell, 1989; Buikstra & Ubelaker, 1994; Iscan, Loth, & Wright, 1984, 1985; Key, Aiello, & Molleson, 1994; Krogman & Iscan, 1986; Lovejoy, 1985; Suchey & Katz, 1986, 1998; Ubelaker, 1999). Most individuals for whom age could be estimated died in middle adulthood (age 30–49 years), which is consistent with a population prior to modern medicine (Goodman, Lallo, Armelagos, & Rose, 1984; Larsen, 1997; Steckel & Rose, 2002; Verano & Ubelaker, 1992; Wood, Milner, Harpending, & Weiss, 1992). Macroscopic examination of pelvic elements were used to estimate sex (Bass, 1981; Buikstra & Ubelaker, 1994; Rogers & Saunders, 1994; Ubelaker, 1999; White, 1991). Individuals were grouped into female, possible female, male, possible male, or indeterminate sex categories, but only female or male individuals were used for sex comparisons in this research.

TABLE 1 List of elbow joints surfaces observed for OA

Joint	Joint surfaces
Elbow (7 surfaces)	1. Capitulum of humerus 2. Trochlea of humerus 3. Head of radius 4. Trochlear notch of ulna 5. Olecranon process of ulna 6. Coronoid process of ulna 7. Radial notch of ulna
Arm (7 elbow + 2 shoulder surfaces)	1. All surfaces in elbow 2. Glenoid fossa of scapula 3. Head of humerus
Leg (2 hip + 6 knee surfaces)	1. Os Coxa acetabulum 2. Head of femur 3. Femur medial condyle 4. Femur lateral condyle 5. Patella medial facet 6. Patella lateral facet 7. Tibia medial condyle 8. Tibia lateral condyle

When evaluating the sample, any individual with evidence of elbow injury was excluded to eliminate trauma-related OA etiology. If the joint surface was otherwise undamaged, at least 90% of each articular surface needed to be visible and intact to score it for OA. Following *Standards* (Buikstra & Ubelaker, 1994:121–123) and Rogers and Waldron (1995), bilateral OA scores were noted as present when each surface of the elbow joint had evidence of one of the following on over at least one-third of the articular surface:

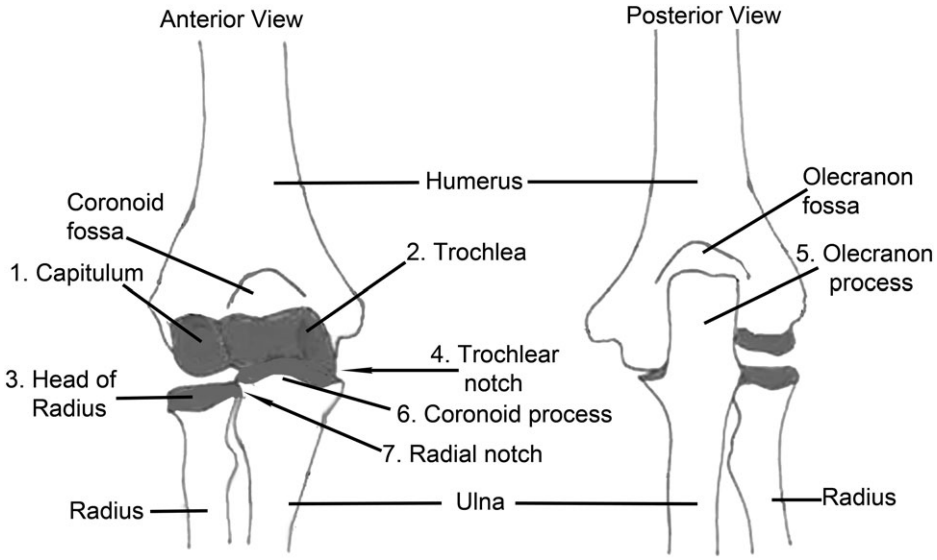

FIGURE 2 Articular surfaces of the elbow joint investigated for this study

pitting or porosity, new bone growth showing osteophytes or new ridges of bone and a joint margin (i.e., lipping), joint contour changes, or bone polishing (i.e., eburnation).

Data were collected for all individuals (e.g., location, presence/absence for OA, age, and sex), entered into an Access database linked by specimen number, and imported into SAS 9.4 in order to run the GEE procedure. SAS was used to separate each of the seven surfaces (e.g., Elbow1 = Capitulum of humerus, Elbow2 = Trochlea of humerus), as well as one tally with all seven surface areas of the elbow combined. The final step in the process included running a variety of comparisons using the population-averaged GEE procedure to look for significant modeled differences at the 0.05 level using the chi-square statistic. These comparisons were also made while statistically controlling for age at death and sex because of concerns about sex- and age-related OA changes in bioarchaeological studies (Jurmain, 1999; Jurmain et al., 2012; Weiss & Jurmain, 2007). In addition, for comparative purposes, data by score and by individual were collected for any evidence of OA on any articular surface in the elbow joint. These data were run by side of the body in a two-by-two contingency table separated by region (Tiwanaku core vs. colony) using chi-square statistic to test for significance. Odds ratio statistical comparisons with generalized mixed effects modeling were also used as a comparison to measure the strength of association between highland core and colony OA data at the 0.05 level.

3 | RESULTS

Prevalence of OA was calculated for the whole sample population by present and absent data points (Table 3). Rates were at 19% for OA overall (14% in the core and 21% in the colony). By side of the body, left OA rates were at 21% overall (19% in the core and 21% in the colony), and right OA rates were 19%, with much lower rates in the core (12%) than the colony (21%). Comparing these data in a two-by-two contingency table, there were no significant results overall and for the left side of the body, but the right side was statistically significant.

To demonstrate the efficacy of GEE, four comparisons were performed between the Tiwanaku core and colony for elbow joint surfaces: (a) all adults, (b) all middle adults age 30–49 at-death (the largest group of individuals for whom age could be estimated) (c) all females, and (d) all males. The left column of the Table 4 results show the comparison for all adults in this case study. The overall seven surfaces combined under the "elbow joint" contain significant differences for the left side of the body between core and colony, as well as in the combined left and right side. In both cases, the core individuals

TABLE 2 Demographic information for individuals in this study

	Age-at-death	Core Bolivia (# of individuals)	Colony Peru (# of individuals)
Adults = 1,195 individuals	Young adult (16–29 years)	69	160
	Middle adult (30–49 years)	126	258
	Older adult (50+ years)	30	44
	Adult, age indeterminate	278	230
	Total	503	692
	Sex of adults	**Core Bolivia (# of individuals)**	**Colony Peru (# of individuals)**
Adults by sex = 590 individuals	Females	76	231
	Males	102	181
	Total	178	412

TABLE 3 Prevalence of elbow joint OA by overall data point and side of the body with 2 × 2 contingency table using the chi-square statistic with Yates' correction for significance

	OA absent (% of the total sample)	OA present (% of the total sample)	2 × 2 contingency table (χ^2)
By present/absent score for Highland Core	1,260 (87%)	198 (14%)	χ^2 = 0.94 *p* value = .3 *not statistically significant
For Moquegua Colony	3,239 (79%)	877 (21%)	
Total	4,499 (81%)	1,075 (19%)	
Left side by present/absent score for Highland Core	508 (81%)	122 (19%)	χ^2 = 1.142 *p* value = .3 *not statistically significant
For Moquegua Colony	1,589 (79%)	434 (21%)	
Total	2097 (79%)	556 (21%)	
Right side by present/absent score for Highland Core	554 (88%)	76 (12%)	χ^2 = 25.75 *p* value < .0001 *statistically significant
For Moquegua Colony	1,643 (79%)	443 (21%)	
Total	2,197 (81%)	519 (19%)	

had higher modeled rates under the GEE procedure. Further, not every joint surface within Table 4 was statistically significant. Instead, the trochlea of the humerus (#2) was significant on the left side of the body and in the combined sample. The radial notch of the ulna (#7) was also significantly different between the core and colony. Both the trochlea and the radial notch had higher modeled percentages in the core sample.

GEE was also used to compare data from the largest Tiwanaku sample for whom age at death could be estimated, those in the middle adult category (30–49 years at death), in order to demonstrate looking at age-related activity changes (Table 4, right column). Results show significant differences in the combined left and right sides of the elbow joint, with higher modeled rates from members of the colony. Further, individual surfaces at the coronoid process (#6) and the radial notch (#7) of the ulna had significant differences. The coronoid process had a difference in the combined results from both sides of the body with higher rates in the core. The left, right, and the combined scores on the radial notch were greater in the core, similar to the overall sample not separated by age.

GEE was also used to look for OA difference by females (Table 5, left column) and males (Table 5, right column). For females, only the left side and the combined left and right side for the radial notch (#7) of the ulna was significant, with higher modeled rates from the colony. Opposite of the female results, the comparison among males had many significant differences between the core and colony in elbow OA rates, which could indicate a greater degree of repetitive movement differences among males within the Tiwanaku state. In the combined sample, males had significant OA differences in the left elbow joint, and in a combined left and right, both with higher modeled percentages from the core. Males also had significant results in five of the seven elbow surfaces: capitulum of the humerus (#1), trochlea of the humerus (#2), head of the radius (#3), trochlear notch of the ulna (#4), and the radial notch of the ulna (#7).

Data were also calculated by individual for the left and right sides of the body using the same criteria as GEE: overall, by the middle adult category, and by sex (Table 6). OA overall rates are greater in the colony than the core for both the left and right sides of the body and both are statistically significant. By age, OA rates were higher for the colony sample although neither side of the body was statistically significant. For females, sample prevalence was higher in the colony and statistically significant on the right side of the body, but not the left side. Rates were also higher for colony males for both left and right sides of the elbow joint but neither was statistically significant. Odds ratio data were also calculated with elbow OA significantly different between the core and colony (Table 7). However, there were no significant differences by the middle age category or by sex, and comparisons could not be performed by side of the body.

Finally, GEE results were calculated for multiple data points in Tiwanaku peoples' arms (shoulder and elbow) and legs (hip and knee) (Table 8). Similar to the results by elbow joint only, OA was significant in the left arm and in combined left and right sides, with greater percentages in the core. Middle adult individuals also had significantly higher rates in the core for all categories. Females had no significant differences, but males had left side and combined side significant results, and core rates were higher.

4 | DISCUSSION

OA has a varied etiology, but when it is used to understand past populations via human skeletal remains, bioarchaeologists have suggested contextualized, population-focused approaches with strong statistical methods. Limiting the potential causes of OA to groups with similar genetic backgrounds, diets, obesity risks, as well as evaluating data by age and sex from this perspective may provide insight to the biomechanical changes, such as mechanical loading and repeated movements, of past groups. How to address scalar concerns and analyze multiple OA data points to achieve useful information and interpretations has been the focus of this article. If data are collected and analyzed by each articular surface, the sheer amount of data could overwhelm understanding. However, if data are totaled for frequency and run with a simple two-by-two contingency table, there are concerns because assumptions of independence could be invalidated as

TABLE 4 All adults for OA in the elbow joint and adults in the middle adult (30–49 years at death) category (bolded are significant)

All elbow joint surfaces—overall % of modeled frequency						All elbow joint surfaces—middle adult % of modeled frequency					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
42%	**28%**	36%	31%	**39%**	**29%**	46%	33%	48%	37%	**46%**	**35%**
(*n* = 1,703) **(*p* = .007)**		(*n* = 1,703) (*p* = .3)		**(*n* = 3,406)** **(*p* = .03)**		(*n* = 913) (*p* = .09)		(*n* = 899) (*p* = .06)		**(*n* = 1812)** **(*p* = .04)**	
Capitulum of humerus % of modeled frequency						Capitulum of humerus % of modeled frequency					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
47%	35%	41%	40%	44%	38%	43%	41%	50%	54%	45%	48%
(*n* = 242) (*p* = .17)		(*n* = 241) (*p* = .96)		(*n* = 483) (*p* = .36)		(*n* = 131) (*p* = .87)		(*n* = 124) (*p* = .77)		(*n* = 255) (*p* = .83)	
Trochlea of humerus % of modeled frequency						Trochlea of humerus % of modeled frequency					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
28%	**13%**	18%	12%	**23%**	**13%**	32%	16%	23%	15%	28%	15%
(*n* = 247) **(*p* = .025)**		(*n* = 250) (*p* = .32)		**(*n* = 497)** **(*p* = .03)**		(*n* = 134) (*p* = .11)		(*n* = 128) (*p* = .44)		(*n* = 262) (*p* = .09)	
Head of radius % of modeled frequency						Head of radius % of modeled frequency					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
36%	20%	19%	23%	27%	21%	43%	27%	8%	27%	26%	27%
(*n* = 210) (*p* = .06)		(*n* = 228) (*p* = .6)		(*n* = 438) (*p* = .44)		(*n* = 109) (*p* = .24)		(*n* = 119) (*p* = .26)		(*n* = 228) (*p* = .89)	
Trochlear notch of ulna % of modeled frequency						Trochlear notch of ulna % of modeled frequency					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
63%	52%	67%	53%	65%	52%	76%	60%	83%	63%	80%	61%
(*n* = 265) (*p* = .2)		(*n* = 258) (*p* = .15)		(*n* = 523) (*p* = .07)		(*n* = 144) (*p* = .26)		(*n* = 138) (*p* = .10)		(*n* = 282) (*p* = .052)	
Olecranon process of ulna % of modeled frequency						Olecranon process of ulna % of modeled frequency					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
26%	26%	32%	32%	28%	27%	21%	28%	31%	42%	27%	35%
(*n* = 236) (*p* = .72)		(*n* = 236) (*p* = .98)		(*n* = 472) (*p* = .89)		(*n* = 126) (*p* = .62)		(*n* = 126) (*p* = .42)		(*n* = 252) (*p* = .42)	
Coronoid process of ulna % of modeled frequency						Coronoid process of ulna % of modeled frequency					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
49%	33%	42%	38%	46%	36%	65%	40%	61%	42%	**63%**	**41%**
(*n* = 242) (*p* = .07)		(*n* = 239) (*p* = .67)		(*n* = 481) (*p* = .14)		(*n* = 128) (*p* = .06)		(*n* = 129) (*p* = .14)		**(*n* = 257)** **(*p* = .04)**	
Radial notch of ulna % of modeled frequency						Radial notch of ulna % of modeled frequency					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
40%	**14%**	**31%**	**16%**	**36%**	**15%**	**42%**	**16%**	**53%**	**18%**	**47%**	**17%**
(*n* = 261) **(*p* = .0003)**		**(*n* = 251)** **(*p* = .04)**		**(*n* = 512)** **(*p* = .0004)**		**(*n* = 141)** **(*p* = .01)**		**(*n* = 135)** **(*p* = .002)**		**(*n* = 276)** **(*p* = .0009)**	

OA on one articular surface may compromise nearby surfaces. Hence, the contingency table information in Table 3 may not be independent and should not be used to evaluate OA data.

Instead, this research suggests using the strong statistical method of GEE, which retains the largest possible sample size while remaining linked to each individual from whom data was recorded (Ghislatta & Spini, 2004). Results show that comparisons between the Tiwanaku core and colony had significant results in the combined surfaces of the elbow joint (Table 4). It also identified two specific surfaces, the trochlea of the humerus and the radial notch of the ulna, as areas with significantly different OA results. Rates for these surfaces were higher in the core than the colony. In general, this could mean biomechanical

TABLE 5 All adult females and males for OA in the elbow joint (bolded are significant)

All elbow joint surfaces—females % of modeled frequency						All elbow joint surfaces—males % of modeled frequency					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
39%	27%	34%	27%	37%	27%	**50%**	**29%**	43%	35%	**47%**	**32%**
(*n* = 947) (*p* = .08)		(*n* = 935) (*p* = .39)		(*n* = 1882) (*p* = .14)		**(*n* = 686) (*p* = .009)**		(*n* = 703) (*p* = .23)		**(*n* = 1,389) (*p* = .02)**	
Capitulum of humerus % of modeled frequency						**Capitulum of humerus % of modeled frequency**					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
44%	40%	41%	38%	43%	39%	**59%**	**30%**	42%	44%	52%	37%
(*n* = 134) (*p* = .7)		(*n* = 134) (*p* = .83)		(*n* = 268) (*p* = .7)		**(*n* = 100) (*p* = .03)**		(*n* = 99) (*p* = .9)		(*n* = 199) (*p* = .18)	
Trochlea of humerus % of modeled frequency						**Trochlea of humerus % of modeled frequency**					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
28%	14%	17%	10%	22%	12%	**35%**	**13%**	25%	13%	**31%**	**3%**
(*n* = 137) (*p* = .15)		(*n* = 143) (*p* = .44)		(*n* = 280) (*p* = .13)		**(*n* = 101) (*p* = .03)**		(*n* = 98) (*p* = .27)		**(*n* = 199) (*p* = .04)**	
Head of radius % of modeled frequency						**Head of radius % of modeled frequency**					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
17%	20%	20%	20%	19%	20%	**50%**	**20%**	20%	26%	34%	23%
(*n* = 118) (*p* = .79)		(*n* = 129) (*p* = .99)		(*n* = 247) (*p* = .89)		(*n* = 83) (*p* = .03)		(*n* = 93) (*p* = .64)		(*n* = 176) (*p* = .24)	
Trochlear notch of ulna % of modeled frequency						**Trochlear notch of ulna % of modeled frequency**					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
71%	48%	62%	47%	67%	48%	75%	55%	81%	61%	**78%**	**58%**
(*n* = 145) (*p* = .09)		(*n* = 137) (*p* = .32)		(*n* = 282) (*p* = .08)		(*n* = 108) (*p* = .15)		(*n* = 109) (*p* = .14)		**(*n* = 217) (*p* = .04)**	
Olecranon process of ulna % of modeled frequency						**Olecranon process of ulna % of modeled frequency**					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
25%	22%	25%	24%	25%	23%	33%	26%	43%	44%	38%	35%
(*n* = 132) (*p* = .82)		(*n* = 128) (*p* = .96)		(*n* = 260) (*p* = .87)		(*n* = 93) (*p* = .54)		(*n* = 98) (*p* = .93)		(*n* = 191) (*p* = .78)	
Coronoid process of ulna % of modeled frequency						**Coronoid process of ulna % of modeled frequency**					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
47%	30%	50%	40%	48%	35%	47%	40%	38%	36%	43%	38%
(*n* = 135) (*p* = .16)		(*n* = 130) (*p* = .46)		(*n* = 265) (*p* = .17)		(*n* = 97) (*p* = .59)		(*n* = 99) (*p* = .87)		(*n* = 196) (*p* = .6)	
Radial notch of ulna % of modeled frequency						**Radial notch of ulna % of modeled frequency**					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
37%	**13%**	23%	13%	**31%**	**13%**	**53%**	**16%**	**47%**	**21%**	**50%**	**18%**
(*n* = 146) (*p* = .01)		(*n* = 134) (*p* = .34)		**(*n* = 280) (*p* = .02)**		**(*n* = 104) (*p* = .002)**		**(*n* = 107) (*p* = .04)**		**(*n* = 211) (*p* = .002)**	

differences among the people who resided at high altitude of the Tiwanaku state, specifically a back and forth hinge motion at the trochlea or a twisting at the radial notch, when compared to colonists in Moquegua, Peru. It may also indicate handedness with the significant results from the left side of the body. In addition, when evaluated by age, people in the Tiwanaku core who died in their 30s or 40s had significantly higher OA rates when both sides of the body were combined for one elbow joint score. The coronoid process and the radial notch articular surfaces were also significant with greater modeled rates of OA in the core. Movements in this joint surface include a

TABLE 6 Side of the body prevalence of elbow joint OA by individual for region, age, and sex 2 × 2 contingency table using the chi-square statistic with Yates' correction for significance

	OA absent (% of the total sample)	OA present (% of the total sample)	2 × 2 contingency (χ^2)
By individual—left side: Highland Core Moquegua colony	46/90 individuals (51%) 110/289 (38%)	44/90 individuals (49%) 179/289 (62%)	χ^2 = 4.301 *p* value = .04 *statistically significant
By individual—right side: Highland Core Moquegua colony	54/90 (60%) 112/298 (38%)	36/90 (40%) 186/298 (62%)	χ^2 = 13.29 *p* value = .0003 *statistically significant
By age—Middle adult (30–49 years at death)	**OA absent (% of the total sample)**	**OA present (% of the total sample)**	**2 × 2 contingency (χ^2)**
Left side: Core Colony	24/51 individuals (47%) 52 / 162 (32%)	27/51 individuals (53%) 110 / 162 (68%)	χ^2 = 3.16 *p* value = .08 *not statistically significant
Right side: Core Colony	23/46 (50%) 50/162 (31%)	23/46 (50%) 112/162 (69%)	χ^2 = 1.142 *p* value = 0.23 *not statistically significant
By sex	**OA absent (% of the total sample)**	**OA present (% of the total sample)**	**2 × 2 contingency (χ^2)**
Left side: Core females Colony females	15/37 individuals (41%) 55/158 (35%)	22/37 individuals (59%) 103/158 (65%)	χ^2 = 0.215 *p* value = .64 *not statistically significant
Core males Colony males	22/41 (54%) 44/115 (38%)	19/41 (46%) 71/115 (62%)	χ^2 = 2.34 *p* value = .13 *not statistically significant
Right side: Core females Colony females	21/37 (57%) 56/150 (37%)	16/37 (43%) 94/150 (63%)	χ^2 = 3.86 *p* value = .0496 *statistically significant
Core males Colony males	21/40 (52%) 48/133 (36%)	19/40 (48%) 85/133 (64%)	$\chi 2$ = 2.8 *p* value = .09 *not statistically significant

hinge motion in the coronoid process and a twisting motion at the radial notch of the ulna. Also worth noting are the high *n*-values these comparisons. While this sample of 1,195 adults may be larger than average in bioarchaeology, the combined elbow joint score for both sides of the body almost tripled the sample size. This demonstrates that GEE could help with smaller sample sizes, common in bioarchaeology. In addition, while the number of individuals in the age-based sample comparison was reduced from of 1,195 to 384 adults, *n*-values still remained strong.

When GEE results were divided by sex (Table 5), the left radial notch was significant for core females, potentially indicating a similar elbow rotation akin to the overall sample and the one divided by age. In comparison, there were many significant elbow differences between core and colony males, with higher modeled OA rates in the core. The potential differences in the pattern of movement among these males is a hinge movement of repetitive flexion and extension (i.e., capitulum, trochlea, radial head, and ulnar trochlear notch) along with the forearm twisting motion (i.e., ulnar radial notch) found throughout this sample. In addition to a reduction in sample size as with the prior age at death sample, it should be noted that GEE was also able to accommodate a wide difference in sample size for sex, with a much larger sample from the colony (412 females and males) versus the core (178 females and males).

Opposite of the GEE data, results by individual show much higher OA rates in the colony than the core. Significant differences were noted overall for both sides of the body, and for females in their right elbow joint. These differences by individual were not seen in GEE comparisons and may indicate problems with this approach by individuals. First, it reduces potential outcomes and interpretations from OA as there is no pattern of elbow joint biomechanics, just a present or absent score by individual. Second, data by individual has the potential to overestimate OA prevalence, as any evidence of bony change may lead to a

TABLE 7 Odds ratio statistical data by region, age, and sex for elbow joint OA

Comparison	Coefficient estimate	Odds ratio	*p* value
Core vs. Colony	−2.404	0.1103	.0012 *statistically significant
Core vs. Colony—Middle age group	0.796	2.216	.072 *not statistically significant
Core vs. Colony—Females	0.255	1.377	.382 *not statistically significant
Core vs. Colony—Males	0.312	1.367	.439 *not statistically significant

*Datasets were too small to look for side of the body differences using odds ratio

TABLE 8 Arm (combined shoulder and elbow data) and leg (combined hip and knee data) comparison data by region, by middle adult category, and by sex (bolded are significant)

Arm surfaces—overall % of modeled frequency						Leg surfaces—overall % of modeled frequency					
L		*R*		Combined		*L*		*R*		Combined	
Core	Core	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
40%	**26%**	35%	28%	**38%**	**27%**	26%	19%	23%	19%	25%	19%
(*n* = 2,106) **(*p* = .005)**		(*n* = 2,138) (*p* = .14)		**(*n* = 4,241)** **(*p* = .01)**		(*n* = 1,384) (*p* = .13)		(*n* = 1,390) (*p* = .4)		(*n* = 2,774) (*p* = .18)	
Arm surfaces—middle adult % of modeled frequency						**Leg surfaces—middle adult % of modeled frequency**					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
46%	**31%**	**45%**	**34%**	**47%**	**33%**	25%	24%	27%	23%	26%	23%
(*n* = 1,131) **(*p* = .03)**		**(*n* = 1,140)** **(*p* = .03)**		**(*n* = 2,271)** **(*p* = .01)**		(*n* = 701) (*p* = .94)		(*n* = 710) (*p* = .47)		(*n* = 1,411) (*p* = .66)	
Arm surfaces—female % of modeled frequency						**Leg surfaces—female % of modeled frequency**					
L		*R*		Combined		*L*		*R*		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
41%	26%	40%	27%	41%	27%	24%	18%	30%	21%	27%	19%
(*n* = 1,060) (*p* = .054)		(*n* = 1,061) (*p* = .11)		(*n* = 2,121) (*p* = .06)		(*n* = 657) (*p* = .43)		(*n* = 687) (*p* = .3)		(*n* = 1,344) (*p* = .34)	
Arm surfaces—male % of modeled frequency						**Leg surfaces—male % of modeled frequency**					
L		R		Combined		L		R		Combined	
Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony	Core	Colony
52%	**28%**	38%	32%	**46%**	**30%**	27%	18%	20%	18%	24%	18%
(*n* = 762) **(*p* = .003)**		(*n* = 799) (*p* = .31)		**(*n* = 1,561)** **(*p* = .02)**		(*n* = 553) (*p* = .15)		(*n* = 555) (*p* = .73)		(*n* = 1,108) (*p* = .28)	

positive score. While researchers can combat this by setting limitations (e.g., only count OA as present if over 40% of the joint is affected), when data are not collected by each articular surface in the joint, methodological reproducibility would have intra- and inter-observer error issues (Waldron & Rogers, 1991; Weiss & Jurmain, 2007). Finally, while easy to use, two-by-two contingency tables are known to have issues with small sample sizes, and akin to this study, problems when the sample has a non-normal distribution. Hence, contingency tables are not strong statistically, nor can they evaluate other factors like age, sex, or multiple areas of the body (Table 8), like GEE can for OA changes. This makes GEE effective to use as multiple combined scores garner a "whole-body" perspective that does not invalidate statistical assumptions of independence or overwhelm with so many data points that very little comprehensive information can be parsed from any significant differences (Becker, 2013, 2017, 2019; Becker & Goldstein, 2017).

Other strong statistical methods, like odds ratio analyses, may also present problems. In this case, even though the sample was large for bioarchaeology, it was not big enough to run the wide range of analyses GEE could (Table 7). Odds ratio comparisons were also able to identify significant differences between the core and colony in the elbow joint, but not the cause, modeled frequency, or even specific articular area of the elbow affected. Thus, commonly used alternative approaches to GEE, by individual and by odds ratio, demonstrate the loss of specific pathology data by individual.

In sum, studying OA changes in human skeletal remains comes with scalar methodological issues about how to evaluate multiple data points collected and effectively analyze them in ways that are helpful to understand past human populations. If researchers adopt the population-based GEE statistical approach, they can generate a large sample size and correlate various measures, such as age at death and sex, while also having a method that is flexible enough to evaluate small sample sizes, missing variables, and non-normal distributions. Demonstrating GEE's value using a prehistoric Tiwanaku population, this article showed that not only can a GEE approach provide an easily understood and non-statistically biased combined score (i.e., "elbow joint"), but also further used to analyze which articular joint surfaces show OA differences. In addition, while this was primarily limited to elbow data analyses between Tiwanaku core and colony people, further GEE combinations were run to see OA prevalence throughout the body. Thus, the GEE procedure is one that should be pursued as a means of analyzing bioarchaeological data with multiple data points and scalar issues.

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